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8.35 MM RADIO EMISSION FROM JUPITER
AND VENUS

by

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Summary

Observations of the 8. 35 mm radio emission from Jupiter and Venus are reported. A disc temperature of $144 \pm 23°$ is found for Jupiter and a temperature of $383 \pm 60°$ is found for Venus. It is shown that the 8 mm brightness temperature of Jupiter should correspond closely to the temperature at the level of the visible cloud cover.

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8. 35 mm Radio Emission from Jupiter and Venus

Introduction

A number of observations of the 8. 35 millimeter radio emission from Jupiter were made following the planet's opposition at the end of August, 1962. A study of the emission of Venus at this wavelength was begun simultaneously, to be carried out through conjunction in November and beyond. The intent of the latter program is the investigation of possible variations of the planet's brightness with either phase angle or time. The results of the Jupiter observations are presented here as well as preliminary results for Venus.

Procedure

The antenna used for these measurements is a ten foot diameter aluminum reflector cast and machined at the U. S. Naval Shipyard in Norfolk, Virginia. The input section of the receiver is located behind the feed horn at the focus in order to avoid feed losses. The gain of the antenna has been measured by locating a transmitter on a nearby hill and comparing the signal received by the antenna with that of a standard gain horn. Because of the height of the hill and that of the antenna above ground and the narrow radiation pattern of the transmitter, no errors due to reflections from the ground are expected. The gain is 5×10^5 with a probable error of 10 per cent.

The radiometer is of the type first described by R. H. Dicke, 1946. The rapid comparison is provided by a ferrite microwave switch at the input. The reference termination consists of a small horn antenna oriented in the same direction as the large antenna, so that the reference temperature, provided by atmospheric absorption, is very close to that of the large antenna. In this circumstance, the effect of changes in receiver gain on the accuracy of the measurements is small. The beam-width of the reference horn is large enough (20°) so that even the presence of the sun within the beam barely alters its temperature. The receiver noise temperature is 2500°, including 0. 4 db insertion loss in the ferrite switch, and its bandwidth is 30 megacycles. The output fluctuation with a 5 second integration time amount to about 1 degree peak to peak or about 0. 2° RMS. A calibration signal is provided by means of a small

amount of noise fed into the receiver through a directional coupler from an argon discharge tube. This signal has been calibrated by comparison with the signals emitted by two matched terminations at different temperatures which were connected to the input of the radiometer in succession. The temperatures of the terminations were regulated and measured to within $0.1^{O}C$. They differed by about $20^{O}C$. The gain stability of the radiometer is 0.1% for 30 minute periods and about 1% for longer intervals.

The manner of observation consists of pointing the antenna West of the planet and allowing the planet to drift through the beam with the antenna stationary. Accurate positioning is accomplished by means of an optical sighting telescope mounted on the edge of the antenna. The sighting telescope was aligned during the gain calibration. Attempts to make measurements by alternately tracking the planet and an empty sector of sky nearby proved unsatisfactory due to the effects of atmospheric absorption at this wavelength. Escept when the planet is near the meridian, its zenith angle changes rapidly enough during any suitable tracking period to make the background sky temperature change significantly. Although this effect is somewhat reduced through the use of the reference horn pointing in the same direction as the main antenna, it remains troublesome.

Results for Jupiter

Because the emission from Jupiter is relatively weak, it could not be seen on individual drift scans. Figure 1 shows the result of averaging 16 scans taken on September 18 and 20. The resulting antenna temperature due to Jupiter is $0.20^{O}K$. The atmospheric absorption was measured and found to be 5% at zero zenith angle. This absorption was inferred from a measurement of antenna temperature as a function of zenith angle. With atmospheric absorption and the slight smoothing of the trace due to the 5 second time constant accounted for, the disc brightness temperature implied by the September 18 and 20 observations is 148°. Further measurements were made on October 1, 4, 29, and 30. The average disc temperature for 16 scans taken on October 1 and 4 is 134° and for 32 scans taken on October 29 and 30 is 146°. The average for all 64 scans is 144°. The probable error due to the residual noise on the traces is 18°. When the systematic error, primarily due to uncertainty in antenna gain, is

added, the total probable error is 23°.

$$T_B = 144^\circ \pm 23^\circ$$

Measurements of Jovian radiation between 3 and 68 cm exhibit a spectrum which differs markedly from that of a black body, the flux density being nearly constant between 10 and 68 cm. These measurements as well as various explanations of them that have been advanced are summarized by Drake, 1961; Mayer, 1961; and Burke, 1961. The spectrum of this longer wavelength radiation as well as its polarization properties and the fact that it appears to fluctuate suggest that it arises from an electron gas surrounding the planet. The disc temperature at 3 cm has been found to be approximately 150°. As pointed out by Drake, 1961, a large part of this probably arises as black body emission from the planetary surface or lower atmosphere. We should therefore expect the radiation at 8 mm to be entirely of this nature.

The available information concerning the atmosphere of Jupiter is summarized by Kuiper, 1952, and more recently by Opik, 1962. In his discussion Kuiper proposes an atmosphere rich in hydrogen and helium with an isothermal stratosphere at 86° extending down to a troposphere in adiabatic equilibrium with the corresponding constant temperature gradient. The visible cloud layer occurs at some level within the troposphere. Small amounts of ammonia and methane are observed above the clouds. The amount of ammonia above the clouds which is inferred from the observed spectrum of sunlight reflected from the clouds is 700 cm-atmospheres at STP. At low temperatures, the vapor pressure of ammonia is quite low, and Kuiper further supposes that the partial pressure of the ammonia at any level above the clouds is limited by the vapor pressure at the corresponding temperature at that level. The ammonia vapor is in equilibrium with the solid phase which forms the visible clouds. The requirement that the visible atmosphere contains the observed abundance of ammonia then fixes the cloud top temperature at about 168°. Direct evidence that the visible atmopshere is primarily composed of hydrogen and helium is provided by the observation by Baum and Code, 1953, of the occultation of σ Arietis by Jupiter. They concluded that the mean molecular weight lay in the range of 2.2 to 4.4 for a stratospheric temperature of 86°.

For the purpose of comparison, we shall estimate the expected planetary disc temperature at 8.35 mm on the basis of Kuiper's model b atmosphere. This atmosphere contains 59.5 per cent helium and 37.7 per cent hydrogen, the remainder including ammonia and methane. The mean molecular weight is 3.26, and the mean ratio of specific heats is 1.56. The corresponding adiabatic temperature gradient is 4.0° per kilometer. The cloud top temperature is 168°, and the pressure there is 2 atmospheres. Ammonia is the one constituent which has appreciable absorption at microwave frequencies due to its inversion band centered at 1.2 cm, so that the 8.35 mm emission will arise from this component alone. As its partial pressure above the clouds is limited by its vapor pressure, its abundance will decrease very rapidly above the clouds with the uniform decrease in temperature. We may therefore ignore the stratosphere and suppose that the adiabatic atmospher extends out to its natural limit of 42 kilometers. The temperature at a height x above the clouds is

$$T = T_c \left(1 - \frac{x}{h}\right) \tag{1}$$

where $T_c = 168°$ and h = 42 km. From the discussion above and the Clausius-Clapeyron equation, the ammonia density above the clouds is

$$n(x) = \frac{n_c T_c}{T} e^{-23\left(\frac{T_c}{T} - 1\right)} \tag{2}$$

where n_c is the density at the cloud tops, chosen so that the total abundance is 700 cm-atmospheres. This makes the relative abundance at cloud tops 1.2×10^{-3}. The half widths of the individual ammonia lines are given by (Birnbaum and Maryott, 1954)

$$\Delta \nu_{JK} = 10^{-2} \left(\frac{288}{T}\right) P_{cm} \left[\frac{K^2}{J(J+1)}\right]^{1/3} \quad \propto \quad n \tag{3}$$

Among the stronger lines the range of half widths is small, and we shall adopt the uniform value of 25 mcs. at 1 mm pressure and T = 288°K. From the assumed abundances of hydrogen and helium and the pressure broadening data of table 13-4 of Townes and Shawlow, 1955, the line width at the cloud tops is 5.1 kmc. We assume that the temperature dependence of $\Delta \nu$ in the mixture is given by (3). Above the clouds the half width is therefore

$$\Delta \nu = \Delta \nu_c \frac{T_c}{T} e^{-23\left(\frac{T_c}{T} - 1\right)} \tag{4}$$

The absorption at any frequency ν due to any line m is given approximately by (Townes and Schawlow, 1955, p. 343)

$$\gamma_m \cong \gamma_m^0 \left(\frac{\nu}{\nu_m}\right)^2 \frac{(\Delta \nu)_m^2}{(\nu - \nu_m)^2 + (\Delta \nu_m)^2} \tag{5}$$

where ν_m is the frequency of the line and the peak intensity γ_m^0 is given in table 12-3 of Townes and Schawlow for pure ammonia. In the mixture $(\gamma_m^0 \Delta \nu)$ remains fixed, so that the peak line intensity at the cloud tops is $1.54 \times 10^{-2} \gamma_m^0$. Above the clouds the peak intensity varies as T^{-2}. The total absorption is the sum of contributions from about 24 strong lines. The optical depth down to a height X above the clouds is given by

$$\tau(X) = \int_X^h \sum \gamma_m \, dx \tag{6}$$

Combining these relations, we have

$$\tau(X) = 1.54 \times 10^{-2} \sum_m \gamma_m^0 \left(\frac{\nu}{\nu_m}\right)^2 (\Delta \nu_c)^2 \int_X^h \left(\frac{T_c}{T}\right)^4 \frac{e^{-46\left(\frac{T_c}{T}-1\right)}}{[(\nu - \nu_m)^2 + (\Delta \nu_c)^2 \left(\frac{T_c}{T}\right)^2 e^{-46\left(\frac{T_c}{T}-1\right)}]} \, dx \tag{7}$$

$$\cong 1.40 \times 10^3 \left(\frac{T_c}{T}\right)^2 e^{-46\left(\frac{T_c}{T}-1\right)} \sum_m \gamma_m^0 \left(\frac{\nu}{\nu_m}\right)^2 \frac{(\Delta \nu_c)^2}{(\nu - \nu_m)^2} \tag{8}$$

provided that $(\nu - \nu_m) \gg (\Delta \nu_c)$. For ν = 36 kmc. (λ = 8.35 mm), the value of the sum is found from table 12-3 of Townes and Schawlow to be 2.64 x 10^{-3}. Therefore,

$$\tau(x) \cong 3.7 \left(\frac{T_c}{T}\right)^2 e^{-46\left(\frac{T_c}{T} - 1\right)} \cong 3.7 e^{-46\left(\frac{T_c}{T} - 1\right)} \tag{9}$$

As the total optical depth down to the clouds is 3.7, we expect the emission temperature to correspond to a level slightly above.

The planetary disc temperature may be estimated as follows. Rewrite (9) so that

$$T(\tau) = T_c \frac{46}{47.3 - \ln \tau} \tag{10}$$

The brightness temperature of a pencil of radiation with the direction cosine μ relative to the normal due to the ammonia above the clouds is

$$T_B(\mu) = \int_0^{\frac{3.7}{\mu}} T(\tau) e^{-\tau/\mu} \frac{d\tau}{\mu} \cong \int_0^{\infty} T(\tau) e^{-\tau/\mu} \frac{d\tau}{\mu} \cong .96 T_c + \frac{T_c}{47.3} \ln \mu \tag{11}$$

except near μ = 0. The disc temperature is then

$$T_D = 2 \int_0^1 T_B(\mu) \mu \, d\mu \cong .95 T_c = 160° \tag{12}$$

The predicted value of 160° is just within the probable error of the observed temperature of 144°. If one were to assume a greater relative abundance of hydrogen to helium, as in the case of Kuiper's model a, 1952, a slightly greater absorption at 8.35 mm would be predicted due to increased pressure broadening. However, the emission temperature would be only slightly changed because the ammonia exists in a very thin layer as indicated by equation (2). In fact, the 8.35 mm temperature should be close to the cloud top temperature for a range of possible atmospheres, so long as: (a) the ammonia is in saturation equilibrium with the solid phase, (b) the amount above the clouds is about 700 cm-atmospheres, and (c) the total pressure at the cloud tops is at least 2 atmospheres, with the atmosphere mostly consisting of hydrogen and helium. In his recent discussion of Jupiter, Öpik, 1962,

has concluded that the cloud top temperature is 156° and the pressure about 11 atmospheres, the main constituent of the visible atmosphere being helium. The 8.35 mm temperature for this model is about 150° which is fairly close to the observed value of 144° reported here. Finally, it should be noted that the requirement of saturation equilibrium for the ammonia implies that there be solid ammonia particles throughout the extent of the gas phase, so that the "cloud tops" do not form a single reflecting layer for visible light. The inferred ammonia abundance of 700 cm-atmospheres (Kuiper, 1952, p. 374) based on a simple reflecting layer model may therefore be somewhat in error.

Results for Venus

Venus was first observed on October 17. An average of 16 scans on that day showed a mean increase in antenna temperature due to Venus of 0.55° (Figure 2). The disc temperature implied by this is

$$T_D = 383 \pm 60°$$

Observations nearer conjunction yielded temperatures which are slightly higher but within the probable error. This result is not significantly different from the value of 410 ± 160° reported by Gibson and McEwan, 1959, at 8.6 mm and the value of 315 ± 70° reported by Kuzmin and Salomonovich, 1960, at 8.0 mm.

Acknowledgement

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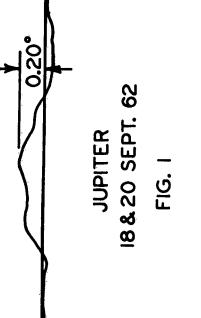
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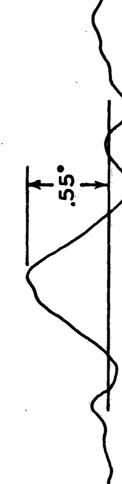KUIPER, G. P. (1952). Planetary atmospheres and their origin. In "The Atmospheres of the Earth and Planets". (G. P. Kuiper, ed.), pp. 306-405.

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Figure 1. The average of 16 drift scans of Jupiter taken on September
18 and September 20. The ordinate is antenna temperature.

Figure 2. The average of 16 drift scans of Venus taken on October 17,
1962, about four weeks before inferior conjunction. The
ordinate is antenna temperature.

BEAM WIDTH

0.20°

JUPITER
18 & 20 SEPT. 62

FIG. I

THORNTON WELCH

BEAM
WIDTH

.55°

VENUS, 17 OCT. 62

FIG. 2

THORNTON WELCH

Appendix

I. Measurement of Atmospheric Absorption

In order to relate the antenna temperature resulting from the presence of the planet in the antenna beam to the planetary disc temperature, the absorption of the earth's atmosphere must be known. Because the signals observed are so weak relative to the background receiver noise, it is difficult to measure the variation of the apparent brightness of the planet with zenith angle and then extrapolate to zero atmospheric air mass. If the sun is in the sky at the time of observation, it may be used for this purpose as it is a very bright source. In its absence the absorption is inferred from observations of the antenna temperature as a function of zenith angle with no extraterrestrial source in the antenna beam.

$$T_A(Z) = \int_0^{\tau_o \sec Z} T(\tau) e^{-\tau \sec Z} \, d\left[\tau \sec Z\right] \qquad (A.1)$$

Z is the zenith angle, $T(\tau)$ is the atmospheric temperature at any optical depth τ above the ground, τ_o is the total (normal) optical depth of the atmosphere. Most of the absorption and consequent emission occurs in the troposphere where the temperature does not differ greatly from the ground temperature. The above equation may then be approximately written

$$T_A(Z) \approx \langle T_s \rangle \left(1 - e^{-\tau_o \sec Z}\right) \qquad (A.2)$$

It is found that this equation fits observations closely with $\langle T_s \rangle = 270^\circ K$. Thus a few observations of $T_A(Z)$ on any given day provide a value for τ_o.

In the present case these measurements are made as follows. The reference horn is oriented at right angles to the main antenna in the meridian plane; that is, the reference horn has the same hour angle as the main antenna but 90° greater declination. Then when the antenna is pointed 45° from the zenith in the meridian plane, both it and the reference horn have the same temperature. A few readings of the temperature difference between the two for a few angles other than 45° then provide τ_o. This procedure has the advantage of simplifying baseline

calibration. It also minimizes the effects of baseline drift due to receiver gain change.

II. Signal Reduction Due to the Output Integrator

Smoothing of the output noise of the radiometer is provided by a double-pole integrator, i. e., two identical simple R-C filters in cascade. When the planet passes through the antenna beam, the radiometer response is somewhat distorted due to the inertia of the integrating circuit. Naturally, this limits the amount of integration time that may be employed relative to the transit time of the source through the antenna beam. The reduction in the maximum response of the radiometer output for this two-pole integrator as a function of the ratio of source transit time to RC has been calculated.[*] RC is the time constant of each pole; the five seconds referred to in the above text corresponds to each pole. The antenna beam-width is 12.0 minutes. With the five second time constant this gives a reduction in the maximum radiometer response of 5 per cent for Jupiter drifting through the beam on October 1, 1962. This value was used to correct the drift curves.

[*]Radiometer Studies and Related Problems, Space Sciences Laboratory Series 4, Issue 22.